

# Experimental Demonstration of a Heralded Entanglement Source

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**The heralded generation of entangled states is a long-standing goal in quantum information processing, since it is indispensable for a number of quantum protocols<sup>1,2</sup>. Polarization entangled photon pairs are usually generated through spontaneous parametric down conversion (SPDC)<sup>3</sup> whose emission, however, is probabilistic. Their applications are generally accompanied with post-selection and destructive photon detection. Here, we report a source of entanglement generated in an event-ready manner by conditioned detection of auxiliary photons<sup>4</sup>. This scheme profits from the stable and robust properties of SPDC and requires only modest experimental efforts. It is flexible and allows to significantly increase the prepa-**

**ration efficiency by employing beam splitters with different transmission ratios. We have achieved a fidelity better than 87% and a state preparation efficiency of 45% for the source. This could offer promising applications in essential photonics-based quantum information tasks, and particularly enables optical quantum computing by reducing dramatically the computational overhead<sup>5,6</sup>.**

Quantum entanglement is one of the key resources in quantum information and quantum foundation. Besides its fundamental interest to reveal fascinating aspects of quantum mechanics, they are also crucial for a variety of quantum information tasks<sup>1,2</sup>. In particular, photonic entangled states are robust against decoherence, easy to manipulate and show little loss, both in fiber and free-space transmission, and thus are exceptionally well suitable for long distance quantum communication and linear optical quantum computing<sup>6,7</sup>. Consequently, an event-ready source for entangled photonic states is of great importance, both from the fundamental and the practical point of views. Entanglement sources based on the probabilistic generation process of SPDC allow for demonstrations of a number of quantum protocols, but do not permit on-demand applications, deterministic quantum computing and significantly limit the efficiency of multi-photon experiments. Alternative solutions, such as the controlled biexciton emission of a single quantum dot<sup>8–10</sup> or the creation of heralded entanglement from atomic ensembles<sup>11</sup>, face severe experimental disadvantages, such as liquid-helium temperature environment and large-volume setups.

There has been considerable progress towards the demonstration of heralded photonic Bell pairs. The scheme by Knill, Laflamme and Milburn (KLM)<sup>12</sup> provides a theoretical breakthrough

as proof that efficient quantum computing is possible with linear optics. Although the KLM scheme allows the nearly non-probabilistic creation of entanglement, the method they use is still intrinsically probabilistic. The fact that the KLM scheme uses a single photon source, perfect photon-number-resolving detectors and moreover requires a large computational capacity makes it barely accessible experimentally. The proposal of Browne and Rudolph<sup>5</sup> comprises a significant advance in achieving experimental implementation by using photonic Bell pairs as the primary resource and experimentally realistic detectors. Using their proposal, the number of optical operations per logical two-qubit gate reduces to  $\sim 100$ , in contrast to the original KLM scheme, which would have  $\sim 100,000$  (refs 5,6,12). Central to such a dramatic improvement is the use of a heralded entanglement source<sup>5,6</sup>.

Various ideas based on conditional detection of auxiliary photons or multi-photon interference were recently proposed to overcome the probabilistic character of SPDC<sup>4,13–18</sup>. Following this line, we demonstrate an experimental realization of a heralded entangled photon source by adopting the proposal of Śliwa and Banaszek<sup>4</sup>. This source provides a substantial advance over the general methods by using linear optics<sup>12,13</sup>. In the experiment, we only use commercial threshold single photon counting modules (SPCM) as detectors and passive linear optics. The source is feasible to support on-demand applications, such as the controlled storage of photonic entanglement in quantum memory<sup>19</sup> to realize the quantum repeater scheme<sup>20</sup>. Moreover, it is suitable to serve on-chip waveguide quantum circuit applications which promise new technologies in quantum optics<sup>21</sup>.

To demonstrate the basic principle of the heralded entangled photon source, we illustrate the scheme of Śliwa and Banaszek<sup>4</sup> in Fig. 1. With an input of SPDC source emitted from modes  $a, b$ , the scheme herald an entangled photon pair in  $c, d$  modes conditioned by triggers of four photons in  $e, f$  modes. As an input of the optical circuit, three-pair component of the down converted photons entangled in polarizations is utilized. The quantum state of the three-pair photon term is given by<sup>22</sup>

$$|\Psi_3\rangle = \frac{1}{12}(\hat{a}_x^\dagger \hat{b}_y^\dagger - \hat{a}_y^\dagger \hat{b}_x^\dagger)^3 |vac\rangle, \quad (1)$$

where  $|vac\rangle$  denotes the vacuum state, and  $\hat{a}^\dagger$  and  $\hat{b}^\dagger$  are the creation operators of photons in the modes  $a$  and  $b$ . Horizontal and vertical polarization are represented by  $x$  and  $y$ , respectively. The optical circuit (see the Methods section) transforms  $|\Psi_3\rangle$  into<sup>4</sup>:

$$|\Psi'_3\rangle = \frac{1}{\sqrt{2}}RT^2|\theta\rangle_{\mathbf{t}}|\Phi^+\rangle_s + \sqrt{1 - \frac{T^4R^2}{2}}|\Gamma\rangle_{ts}. \quad (2)$$

The first term of Eq. (2) is composed of a tensor product of two states: the state  $|\theta\rangle_{\mathbf{t}} = \hat{e}_x^\dagger \hat{e}_y^\dagger \hat{f}_{x'}^\dagger \hat{f}_{y'}^\dagger |vac\rangle$  denoting one photon in each of the four trigger modes, and the maximally entangled photon pair in the output modes

$$|\Phi^+\rangle_s = \frac{1}{\sqrt{2}}(\hat{c}_x^\dagger \hat{d}_x^\dagger + \hat{c}_y^\dagger \hat{d}_y^\dagger) |vac\rangle. \quad (3)$$

The normalized state  $|\Gamma\rangle_{ts}$  is a superposition of all states that do not exactly have one photon in each of the trigger mode  $\hat{e}_x, \hat{e}_y, \hat{f}_{x'}$  and  $\hat{f}_{y'}$ . Hence, the scheme for heralded entanglement source is clearly based on the fact that when detecting a coincidence of four single photons in the trigger modes  $(\hat{e}_x, \hat{e}_y; \hat{f}_{x'}, \hat{f}_{y'})$ , the two photons in the output modes  $(\hat{c}_x, \hat{c}_y)$  and  $(\hat{d}_x, \hat{d}_y)$  nondestructively collapse to the maximally entangled state  $|\Phi^+\rangle_s$ .

In the experiment, we will generate the three-pair photon states (1) by a photon source (see

the Methods section) and consequently implement the transformation of the linear optical circuit. A schematic diagram of our experimental set-up is shown in Fig. 2, which is based on the proposal of Ref. 4.

When taking all of experimental imperfections into account (see the Methods section), it is crucial to evaluate the performance this source. Therefore, we have measured the state preparation efficiency and its fidelity, where the efficiency is defined by the number of heralded photon pairs created from the source per trigger signal. For an ideal case, one trigger signal of a fourfold single-photon coincidence perfectly heralds one photon pair creation. In our experiment performed with standard SPCMs, obviously, additional terms yielding triggers will thus result in a reduction of the preparation efficiency. To overcome this obstacle, we limit their emergence by decreasing the transmission coefficients of the beamsplitter. In this regime, the probability of transmitting more than the minimum number of photons to the trigger becomes lower and as such, the danger of under counting photons in the trigger detectors decreases. However, enhancing the preparation efficiency in this way will lower the over all preparation rate.

In order to show the relation between the efficiency of state preparation and the transmission coefficients of the partial reflecting beam splitters, we have chosen BS with three different reflection/transmission ( $R/T$ ) ratios: 48.6/51.4, 57.0/43.0 and 68.5/31.5 in the experiment (Fig. 2). In what follows we will denote them by 50/50, 60/40 and 70/30, respectively, for short. This relation is shown in Fig. 3. The experimental efficiency can be straightforwardly represented as the following relation by the number of triggers  $n_t$ , the average detection efficiency  $\eta_s$  for output states, the

number of six-fold coincidences  $n_s$  among four trigger modes and two output modes

$$\text{eff}_{exp} = \frac{n_s}{n_t \eta_s^2}. \quad (4)$$

For each experimental detection efficiencies  $\eta_s$  and  $R/T$  ratio: 0.129 (50/50), 0.133 (60/40) and 0.15 (70/30), the average coincidence counts  $(n_s, n_t)$  observed per 10 hours are: (37, 9710), (37, 4940) and (14, 1347), respectively. As can be seen from Fig. 3, the experimental results are highly consistent with theoretical estimation (see Supplementary Information):

$$\text{eff}_{theory} = \frac{R^2}{(1 - \eta_t T/2)^2}, \quad (5)$$

where  $\eta_t$  represents the average detection efficiency for trigger photons. Thus, with this setup we have significantly improved the preparation efficiency in comparison with the one provided by the standard procedure through SPDC. One can consider single input pulses of UV laser and output photon pairs of SPDC as trigger signals and output states, respectively. The probability of generating one entangled photon pair per UV pulse means the preparation efficiency of the standard procedure through SPDC<sup>22</sup>.

To quantify the entanglement of the output photons and evaluate how the prepared state is similar to the state  $|\Phi^+\rangle_s$ , we have determined the state fidelity by analyzing the polarization state of the photons in the modes  $(\hat{c}, \hat{d})$  in the three complementary bases: linear ( $H/V$ ), diagonal ( $+/-$ ), and circular ( $R/L$ ). For an experimental state  $\hat{\rho}$ , the fidelity is explicitly defined by

$$\begin{aligned} F &= \text{Tr}(\hat{\rho} |\Phi^+\rangle_{ss} \langle \Phi^+|) \\ &= \frac{1}{4}(1 + \langle \hat{\sigma}_x \hat{\sigma}_x \rangle - \langle \hat{\sigma}_y \hat{\sigma}_y \rangle + \langle \hat{\sigma}_z \hat{\sigma}_z \rangle), \end{aligned} \quad (6)$$

where  $|\Phi^+\rangle_{ss}\langle\Phi^+| = \frac{1}{4}(\hat{I} + \hat{\sigma}_x\hat{\sigma}_x - \hat{\sigma}_y\hat{\sigma}_y + \hat{\sigma}_z\hat{\sigma}_z)$ ,  $\hat{\sigma}_z = |H\rangle\langle H| - |V\rangle\langle V|$ ,  $\hat{\sigma}_x = |+\rangle\langle +| - |-\rangle\langle -|$  and  $\hat{\sigma}_y = |R\rangle\langle R| - |L\rangle\langle L|$ . Eq. (6) implies that we can obtain the fidelity of the prepared state  $\hat{\rho}$  by consecutively carrying out three local measurements  $\hat{\sigma}_x\hat{\sigma}_x$ ,  $\hat{\sigma}_y\hat{\sigma}_y$  and  $\hat{\sigma}_z\hat{\sigma}_z$  on the photons in the output modes  $(\hat{c}_x, \hat{c}_y)$  and  $(\hat{d}_x, \hat{d}_y)$  (see the Methods section). In the experiment, we only used threshold SPCMs to perform measurements. The experimental results are shown in Fig. 4. The experimental integration time for each local measurement, with respect to different reflection/transmission ratio of the BS, took about: 19 h (50/50), 17 h (60/30) and 36 h (70/30). For all three splitting ratios, we recorded more than about 50 events of desired six-photon coincidences for each local measurement:  $\sim 65$  (50/50),  $\sim 58$  (60/30) and  $\sim 62$  (70/30). As can be seen from Table 1, the measured values for the fidelity are sufficient to violate CHSH-type Bell's inequality<sup>23</sup> for Werner states by three standard deviations. Since we only used threshold SPCMs as detectors, the measured coincidences are then affected by unwanted events. In our experiment, the effect of the dark count rate in the detectors on the six-fold coincidence is rather small. (About the dark count contribution, the main part is that one detector is triggered by dark counts, and the other five detectors are triggered by the down conversion photons. Given a three-pair state, the probability of generating a six-fold coincidence count within any particular coincidence window is about  $S \sim \eta^6$ , whereas the leading dark count contribution is about  $S_d \sim \eta^5 D$ , where  $D = n_d t$ ,  $n_d$  is the average dark count rate of detector, and  $t$  denotes the coincidence window. In our experiment, we have  $n_d \sim 300$  Hz and  $t = 12 \times 10^{-9}$  sec. Then it is clear that the dark count rate in detectors contribute a very small part of the six-fold coincidences:  $S_d/S = n_d t / \eta \sim 2 \times 10^{-5}$ . Here  $\eta = 15\%$  is used for the estimation.)

In conclusion, we have demonstrated a heralded source for photonic entangled states, which

is capable of circumventing the problematic issue of probabilistic nature of SPDC. Such source is based on the well known technique of type-II SPDC, which is robust, stable and needs only modest experimental efforts by using standard technical devices. Photon number resolving detectors are not involved in the setup, and therefore we do not endure the restriction inherent to other schemes for implementing heralded entanglement sources<sup>13,15</sup>. To evaluate the performance of our source, we have measured the fidelity of the output state, and demonstrated the relation between the amplitude reflection coefficient of the used beam splitters and the preparation efficiency of the source. A fidelity better than 87% and a state preparation efficiency of 45% are achieved. For future applications, the simple optical circuit of our source could be miniaturized by an integrated optics architecture on a chip using the silica-on-silicon technique<sup>24</sup>. Using waveguides instead of bulk optics would be beneficial to stability, performance and scalability<sup>21,25</sup>. We note that during the preparation of the manuscript presented here, we learned of a parallel experiment by Barz *et al.*<sup>26</sup>.

## Methods

**Optical circuit.** The transformation of the optical circuit consists of BS and HWP operations. The BS operation describes the following transformation of the annihilation operators of the modes  $\hat{a}_k$  and  $\hat{b}_k$  (note that we use annihilation operators to denote the corresponding modes):  $\hat{a}_k = \sqrt{R}\hat{c}_k + \sqrt{T}\hat{e}_k$  and  $\hat{b}_k = \sqrt{R}\hat{d}_k + \sqrt{T}\hat{f}_k$ , for  $k = x, y$ .  $R$  ( $T$ ) is the amplitude reflection (transmission) coefficient of the BS. For the modes  $\hat{f}_x$  and  $\hat{f}_y$ , the transformation of HWP at  $-22.5^\circ$  is defined by:  $\hat{f}_x = (\hat{f}_{x'} - \hat{f}_{y'})/\sqrt{2}$  and  $\hat{f}_y = (\hat{f}_{x'} + \hat{f}_{y'})/\sqrt{2}$ . The optical circuit is able to prevent false signals rising from two-pair emission. This is an important feature of the scheme<sup>4</sup> since the creation



probabilities for two pairs are much larger than for three pairs. Furthermore, contributions from the higher order terms of SPDC can be limited by controlling the corresponding creation probabilities<sup>4</sup>. It is also worth noting that for a given three-pair photon state, the probability of creating a heralded entangled state, i.e.,  $T^4 R^2/2$ , is controllable by changing the transmission coefficients of the BS, which can be up to  $\sim 0.011^4$ .

**Photon source.** The required photon pairs are generated by type-II SPDC from a pulsed laser in a  $\beta$ -Barium-Borate (BBO) crystal. Here, we use a pulsed high-intensity ultraviolet (UV) laser with a central wavelength of 390 nm, a pulse duration of 180 fs and repetition rate of 76 MHz. For an average power of 880 mW UV light and after improvements in collection efficiency and stability of the photon sources, we observe  $\sim 80 \times 10^3$  photon pairs per second with a visibility of  $\mathcal{V} = (91 \pm 3)\%$  measured in the diagonal  $(+/-)$  basis. (The visibility is defined by  $\mathcal{V} = (N_d - N_{ud})/(N_d + N_{ud})$ , where  $N_d$  ( $N_{ud}$ ) denotes the number of two-fold desired (undesired) coincidence counts. Then there exists a direct connection between visibility and fidelity of a measured state  $\hat{\rho}$ :  $F = \text{Tr}(\hat{\rho} |\Psi^-\rangle\langle\Psi^-|) = \frac{1}{4}(1 + \mathcal{V}_x + \mathcal{V}_y + \mathcal{V}_z)$ , where  $\mathcal{V}_k$  for  $k = x, y, z$  denotes the visibility of photon pair in the diagonal, circular, and linear bases, respectively. Here  $|\Psi^-\rangle$  is the singlet Bell state.) Then the probability of creating three photon pairs is about  $5.7 \times 10^{-5}$  per pulse, which is  $\sim 33$  times larger than that of the next leading order term. The estimation of the three-pair creation probability per pulse is based on the experimental pair generation rate and the theoretical  $n$ -pair creation probability<sup>22</sup>  $p_n = (n + 1) \tanh^{2n} r / \cosh^4 r$ , where  $r$  is a real-valued coupling coefficient. From the two-fold coincidence measurement result, the experimental pair generation rate is  $p' = (80 \times 10^3)/(0.15^2 \times 76 \times 10^6) \approx 4.7\%$ . We assume that  $p_1 = p'$ ,  $r$  can directly be

derived from  $p_1$ . Thus the estimated creation probability  $p_3$  and  $p_4$  are obtained.

**Experimental imperfections.** With single photon resolving detectors and 100% detection efficiency, one can see that the three-pair state can provide a maximally entangled photon pair in the output modes deterministically with a 100% probability, if and only if the remaining photons give rise to a fourfold coincidence among the four trigger modes. With the widely used standard SPCM, one cannot discriminate pure single photons from multi-photons which in reality leads to a significant problem of under counting photons. Accordingly, the trigger detectors can herald a successful event even though more than two photons from either mode  $(\hat{a}_x, \hat{a}_y)$  or  $(\hat{b}_x, \hat{b}_y)$  or both have been transmitted to the trigger channels. Furthermore, experimentally we were only able to obtain an average detection efficiency of about  $\eta = 15\%$  resulting from limited collection and detector efficiencies. Here the mean detection efficiency is averaged over the coupling efficiency of eight fibre couplers and the quantum efficiency of the detectors. In addition to the imperfect detections, there are two other factors that affect the performance of our source: the non-ideal quality of the initially prepared pairs and the higher-order terms of down-converted photons. For perfectly created pairs, destructive two-photon interference effects<sup>27–29</sup> will extinguish the contribution of two-pair emission to the trigger signal. With an experimental visibility of  $(91 \pm 3)\%$  imperfectly created states may still give rise to a contribution of two-pair events that leads to the detection of the auxiliary triggers. In addition, four-pair emission can again contribute to both the triggers and the output. Although the experimentally estimated creation probability for a four-pair emission is only  $\sim 1.7 \times 10^{-6}$  per pulse and is much smaller than the probability for a three-pair photon state  $\sim 5.7 \times 10^{-5}$  per pulse, four-pair contribution can lead to an error of the theoretical estimation of

the expected preparation efficiency of about 4.5%. The four-pair contribution is evaluated in the same way as the three-pair state, where the limited detection efficiency of the trigger detectors is considered in the calculation (see Supplementary Information). In Fig. 3, the fluctuations of our experimental data mainly result from the intrinsic statistics of detector counts, and the stability of optical alignment.

**Experimental fidelity  $F$ .** Every expectation value for a correlation function is obtained by making a local measurement along a specific polarization basis and computing the probability over all the possible events. For instance, to get the expectation value of  $RR$  correlation  $\text{Tr}(\hat{\rho} |RR\rangle\langle RR|)$ , we perform measurements along the circular basis and then get the result by the number of coincidence counts of  $RR$  over the sum of all coincidence counts of  $RR$ ,  $RL$ ,  $LR$  and  $LL$ . All the other correlation settings are performed in the same way. The fidelity  $F$  can then directly be evaluated.

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**Author Contributions** C.W., X.-H.B., Y.-A.C., Q.Z., and J.-W.P. designed the experiment. C.W., C.-M.L., A.R., A.G., Y.-A.C., and K.C. performed the experiment. C.W., C.-M.L., A.R., X.-H.B., K.C., and J.-W.P. analyzed the data. C.W., C.-M.L., K.C. and J.-W.P. wrote the paper.

**Competing Interests** The authors declare that they have no competing financial interests.

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**Figure 1 Schematic setup.** The heralded generation of entangled photon pairs is implemented with the optical circuit composed of non-polarizing partial reflecting beam splitters (BS), a half wave plate (HWP) and two polarizing beam splitters (PBS). The BS split mode  $\hat{a}$  ( $\hat{b}$ ) into a trigger mode  $\hat{e}$  ( $\hat{f}$ ) and an output mode  $\hat{c}$  ( $\hat{d}$ ). The auxiliary trigger photons are detected in  $(\hat{f}_{x'}, \hat{f}_{y'})$  in the diagonal  $(+/-)$  basis and in  $(\hat{e}_x, \hat{e}_y)$  in the linear  $(H/V)$  basis. The setup will output an entangled photon pair after successful triggering of the four auxiliary photons.

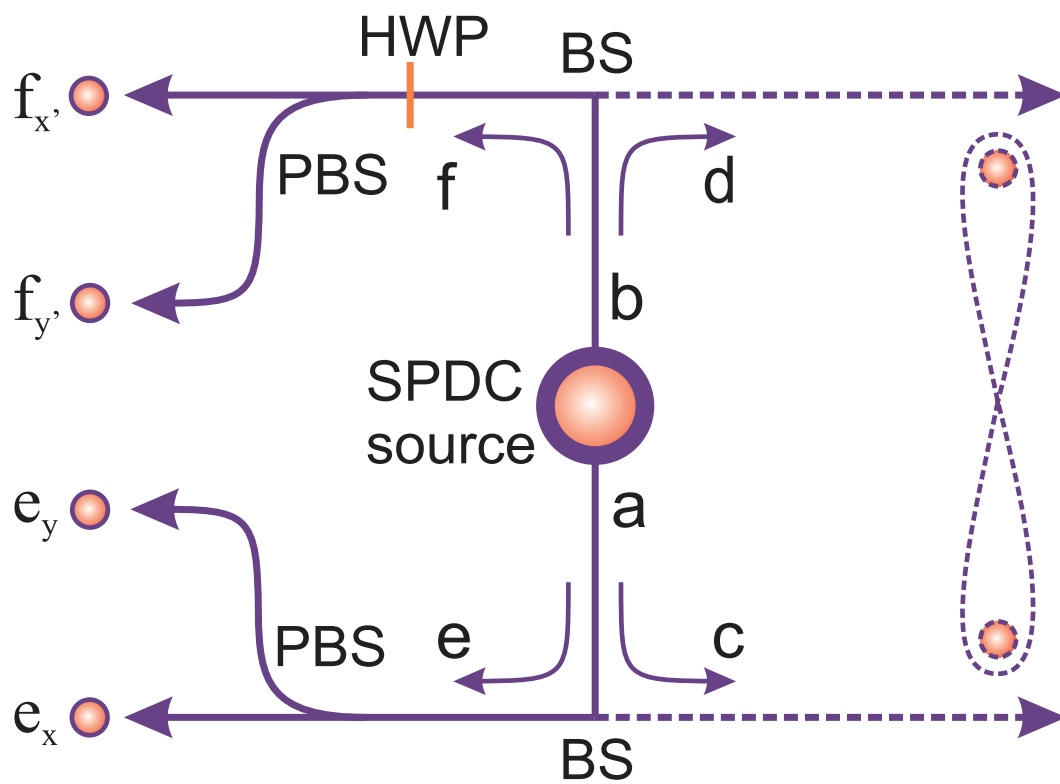
**Figure 2 Experimental setup for event-ready entanglement source.** After emission, the longitudinal and spatial walk-off of the photons in mode  $\hat{a}$  and  $\hat{b}$  will be compensated by a HWP and a correction BBO (C BBO) before the photons are directed onto the partial reflecting beamsplitter (PRBS). To control the additional phase introduced by the PRBS we used a combination of two quarter-wave plates (QWP) and one HWP. All photons are filtered by narrow bandwidth filters ( $\Delta\lambda \approx 3.2$  nm) and are monitored by silicon avalanche single-photon detectors. Coincidences are recorded by a laser clocked FPGA (Field Programmable Gate Array) based coincidence unit.

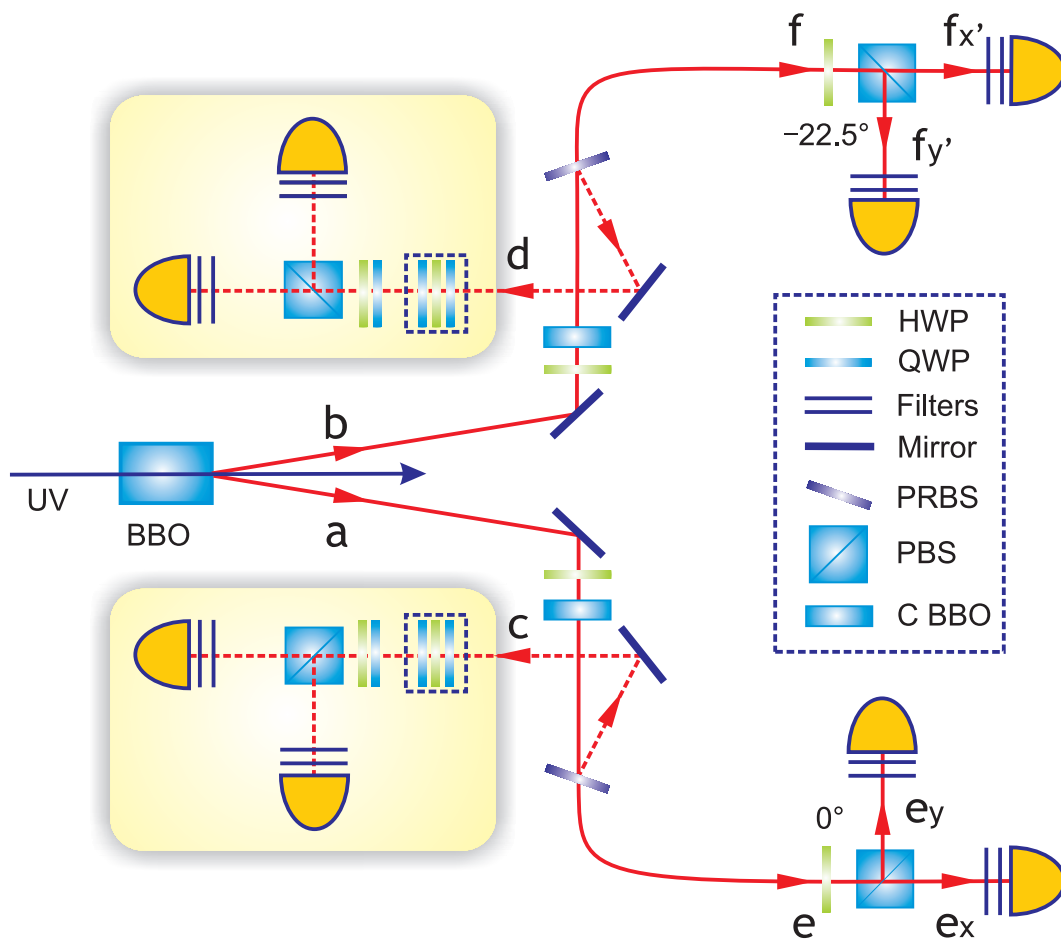
**Figure 3 Efficiency of state preparation.** Theoretical and experimental values of preparation efficiency for the amplitude reflection coefficients  $R = 0.486, 0.570$  and  $0.685$  are depicted. The error bars are according to Poissonian statistics of counts. The curve is a function graph of Eq. 5 with an average detection efficiency  $\eta_t = 0.1823$  for triggers.  $\text{eff}_{theory}$  is an increasing function of  $R$  and up to 100%. The quantum efficiency of detectors  $q$  used is about 60%. For each 50/50, 60/40, and 70/30 BS ratio, our experimental coupling efficiencies of trigger ( $p_t$ ) and signal detectors ( $p_s$ ) are as follows,  $(p_t, p_s)$ : (27.8%, 21.5%), (28.8%, 22.2%), and (34.5%, 25.0%),

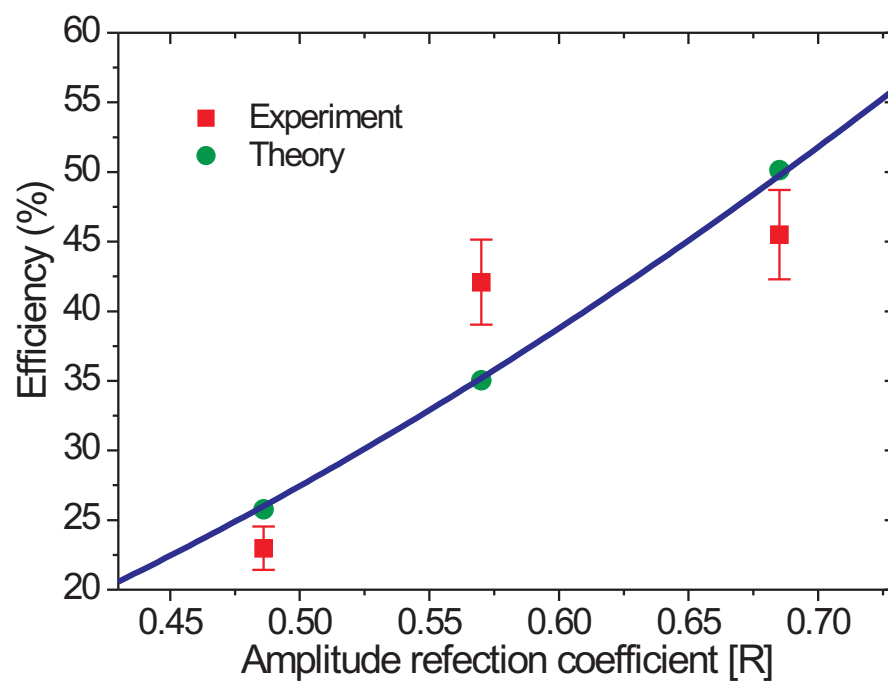


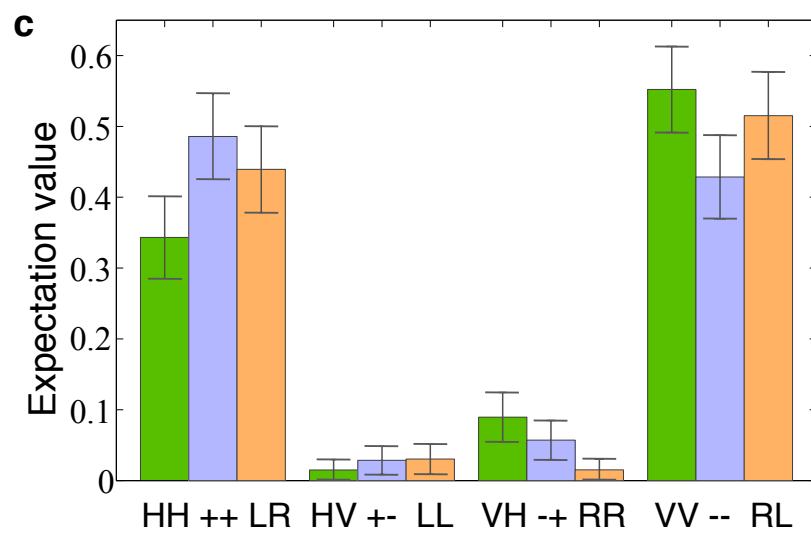
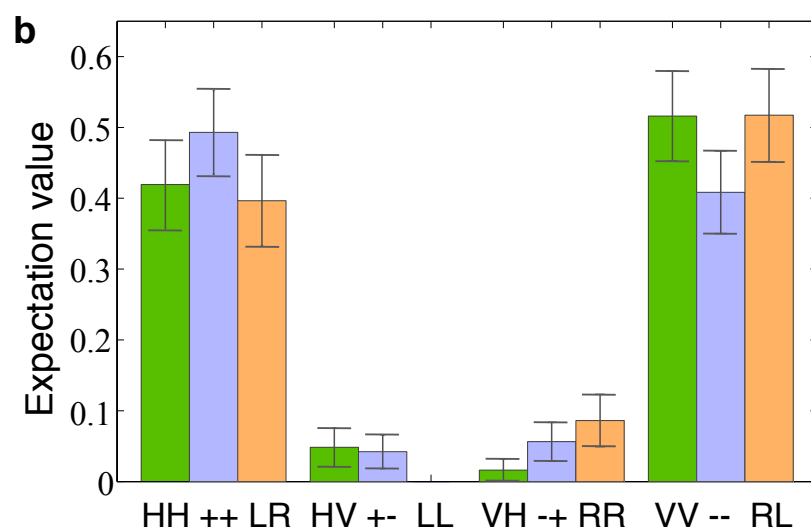
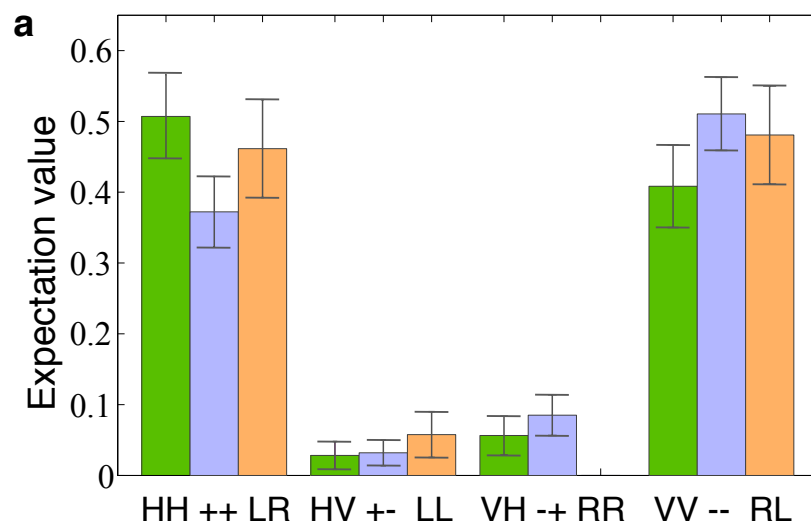
respectively. Note that  $pq$  is defined as the detection efficiency  $\eta$ .

**Figure 4 Experimental data for fidelity measurements.** We have performed a complete 3-setting local measurements for  $\hat{\sigma}_z\hat{\sigma}_z$ ,  $\hat{\sigma}_x\hat{\sigma}_x$  and  $\hat{\sigma}_y\hat{\sigma}_y$ , which corresponding to three complementary bases of  $|H\rangle/|V\rangle$ ,  $|+\rangle/|-\rangle$  and  $|R\rangle/|L\rangle$ , with  $|+\rangle = (|H\rangle + |V\rangle)/\sqrt{2}$ ,  $|-\rangle = (|H\rangle - |V\rangle)/\sqrt{2}$ ,  $|R\rangle = (|H\rangle + i|V\rangle)/\sqrt{2}$  and  $|L\rangle = (|H\rangle - i|V\rangle)/\sqrt{2}$ . The plots are for three different splitting ratios R/T of the partial reflecting beamsplitters 50/50 (**a**), 60/40 (**b**) and 70/30 (**c**). The error bars relate to Poissonian statistics of counts.









Reflection coefficient ( $R$ )	Fidelity
0.486	$0.870 \pm 0.028$
0.570	$0.875 \pm 0.030$
0.685	$0.882 \pm 0.028$

Table 1: Experimental fidelity of the entangled output state with respect to the reflection coefficients  $R$  of the beam splitters.

# Experimental Demonstration of a Heralded Entanglement Source

## Supplementary Information

### Efficiency of state preparation $\text{eff}_{theory}$

In order to show a clear picture of the theoretical estimation, let us consider first the case that we have ideal detection efficiency of 100%. Eq. (5) will be naturally derived afterwards. It is instructive to start with the output state  $|\Psi'_3\rangle$  in the following complete form:

$$|\Psi'_3\rangle = \alpha |\theta\rangle_{\mathbf{t}} |\Phi^+\rangle_{\mathbf{s}} + \beta |\vartheta\rangle_{\mathbf{ts}} + \gamma |\varphi\rangle_{\mathbf{ts}}. \quad (\text{S1})$$

For the first term of Eq. (S1), as already indicated in Eq. (2), the appearance of the perfect four-photon trigger state  $|\theta\rangle_{\mathbf{t}}$  will herald a photon pair in state  $|\Phi^+\rangle_{\mathbf{s}}$  in the output with a probability of 100%. The second term  $\beta |\vartheta\rangle_{\mathbf{ts}}$  represents all additional states, which actually yield a trigger signal in all of the  $(\hat{e}_x, \hat{e}_y)$  and  $(\hat{f}_{x'}, \hat{f}_{y'})$  modes generated by more than four photons, but the state in the output  $(\hat{c}_x, \hat{c}_y)$  and  $(\hat{d}_x, \hat{d}_y)$  contains only a single photon or vacuum. For completeness, the last term  $\gamma |\varphi\rangle_{\mathbf{ts}}$  represents states, which do not contribute to the trigger, but contain more than two photons in the output modes. These states do not affect our experimental results since without trigger signal their contribution is not recorded. All normalization factors are summarized in  $\alpha$ ,  $\beta$  and  $\gamma$ . Therefore, according to the definition of the efficiency of state preparation, we obtain the state preparation efficiency for perfect detections:  $\text{eff}_{theory} = \alpha^2/(\alpha^2 + \beta^2) = R^2/(1 - T/2)^2$ . Now we proceed to discuss the effect of imperfect detection. First, we introduce the detection loss of coupling by replacing the creation operators in the trigger modes  $\hat{\mathbf{t}}^\dagger$  for  $\mathbf{t} = e_x, e_y, f_{x'}, f_{y'}$  with

$\sqrt{p}\hat{\mathbf{t}}^\dagger + \sqrt{1-p}\hat{\mathbf{t}}^\dagger$ , where  $p$  denotes the coupling efficiency for the trigger photons<sup>4</sup>. The operators  $\hat{\mathbf{t}}^\dagger$  describe photons that escape from detections. Then we consider all the components of the state  $|\Psi'_3\rangle$  that can be collected into trigger detectors, e.g.,  $\beta'p^2\sqrt{1-p}\hat{d}_x^\dagger\hat{e}_x^\dagger\hat{e}_x^\dagger\hat{e}_y^\dagger\hat{f}_{x'}^\dagger\hat{f}_{y'}^\dagger|vac\rangle$ . Meanwhile, we take the efficiency of detector into account. For each considered term, we therefore can obtain the corresponding probability of giving a herald signal from its probability amplitude and state vector. For example, for the term illustrated above the probability is  $\beta'^2q^4p^4(1-p)$ , where  $q$  denotes the efficiency of trigger detector. Finally, by the probability of measuring a heralded photon pair over the total probability of generating a trigger signal, we have  $\text{eff}_{theory} = R^2/(1-pqT/2)^2$ . Here  $pq$  is defined as the detection efficiency for trigger photons  $\eta_t$ . For each 50/50, 60/40 and 70/30 BS ratios, our experimental detection efficiencies achieve: 0.167, 0.173 and 0.207, respectively.